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REPORT NO. 775

~~SEPTEMBER 1951~~

(6) RESPONSE OF AIR BLAST GAUGES OF VARIOUS SHAPES TO ONE-POUND SPHERICAL PENTOLITE CHARGES AS A FUNCTION OF PRESSURE LEVEL

(10) Spence T. Marks

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BALLISTIC RESEARCH LABORATORIES

ABERDEEN PROVING GROUND, MARYLAND

(050 750)

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REPORT NO. 775

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Aberdeen Proving Ground, Md.
September 1951

RESPONSE OF AIR BLAST GAUGES OF VARIOUS SHAPES TO ONE-POUND SPHERICAL PENTOLITE CHARGES AS A FUNCTION OF PRESSURE LEVEL

ABSTRACT

The nonlinear pressure response of tourmaline air-blast gauges of various shapes to one-pound spherical pentolite charges has been investigated by comparing peak pressures recorded by the gauges, based upon the extrapolated values of the effective dynamic calibrations at zero peak pressure, with absolute pressures obtained from velocity measurements of shock-front propagation. The peak pressure range of 10 to 80 pounds has been covered. The response errors involved have been calculated from theoretical considerations, and the totals of these errors compared with the recorded errors. A comparison has been made with the results previously reported from one-eighth pound spherical pentolite charges.

INTRODUCTION

Among other characteristics, linearity of response is an important specification for an air-blast gauge; that is, the response should be directly proportional to the pressure applied.

The responses of tourmaline air-blast gauges are linear when they are "statically calibrated." This is a procedure in which the gauge is placed in a pressure chamber having a cellophane window. Air pressure is applied to the chamber until the desired pressure level is reached. The cellophane window is then punctured, and the gauge response is applied to an oscillograph. The resulting trace is photographed, and the response of the gauge is evaluated by comparing the amplitude of the trace with the amplitudes of a series of calibration steps. The calibration steps are produced by applying known voltages to precision condensers, and then discharging the condensers into the circuit.

Air-blast gauges are used edge-on in field work, since the amplitude of the pressure-time trace is used to determine the "peak pressure" of the shock wave, and the duration of the positive phase of the pressure-time trace gives an indication of the shock wave duration. Both of these parameters are important factors in determining the damage that will be caused by a given explosive charge.

When used in this fashion in field work, the responses of air-blast gauges are non-linear; that is, the responses are progressively reduced as the peak pressure level is increased. This non-linear response has been attributed to two errors, namely "gauge-size error" and "high frequency response error."[1] The gauge-size error is a function of the diameter of the sensitive element of the gauge and the shock duration, the latter varying with the charge weight and the distance from the charge. For a given shock duration, the smaller the diameter of the sensitive element, the less the gauge-size error, the minimum diameter in practice being determined by the sensitivity requirements of the recording system. The high frequency amplifier response error is a function of the frequency response of the recording amplifier and the frequencies that are applied to the gauge. Both of these errors have the effect of rounding off the peaks of the pressure-time traces.

The shock tube is an instrument which can be used to test the response of air-blast gauges. Essentially it consists of two cylindrical sections, placed end to end, and separated by a cellophane diaphragm. The air-blast gauge is mounted edge-on near the middle of the open-ended section, and compressed air is allowed to enter the closed end section. The cellophane

1. "Design and Use of Piezoelectric Gauges for Measurement of Large Transient Pressures"; A. B. Arons and R. H. Cole; Review of Scientific Instruments; January, 1950

diaphragm is then punctured and the escaping air produces a shock wave which travels down the tube, causing the air-blast gauge to respond. This instrument has the advantage that both the gauge-size error and the high frequency amplifier response error are eliminated since a step function is produced, the amplitude of which can be measured accurately even though the corner of the step function may be rounded off.

When air-blast gauges are calibrated in a shock tube, however, their responses are also found to be non-linear.[1,2] This reduced response has been attributed to a "flow-effect" around the gauge housing, essentially a Bernoulli effect; consequently it is believed that this flow-effect error can be reduced by equipping the gauge with a baffle designed to reduce the perturbation of the blow behind the shock front to a minimum.[3]

Air-blast gauge response data were needed by this laboratory in connection with the design and development of air-blast gauges which are relatively free from response errors up to Mach 1 (57 lb/in^2 peak pressure), and field tests were conducted in order to obtain the desired information since, as previously stated, the shock tube measures the magnitude of the flow-effect error alone. Moreover, the peak pressure range which could be covered with the five-inch shock tube available to this laboratory was limited to from 3 to 15 lb/in^2. Also, the diameter of the gauges was equal to four-fifths of the diameter of the shock tube, which would make the results suspect because of reflections from the wall of the shock tube.

The results of the first series of tests, employing one-eighth pound bare spherical pentolite charges, have been previously reported.[4]

The recording amplifiers of the Princeton Trailer,[5] which was used for the first series of tests, had poor frequency characteristics due to filters which were installed to suppress radio interference at 17,800 cycles in connection with another testing program.

---

1. "Characteristics of Air-Blast Gauges: Response as a Function of Pressure Level"; A.B. Arons, C.W. Tait, G.K. Fraenkel, and K.M. Doane; NDRC, Div. 2, AES-8a, OSRD-4875a; 1945.

2. "Characteristics of Air-Blast Gauges, II: Response as a Function of Pressure Level"; C.W. Tait and W.D. Kennedy; NDRC, Div. 2, AES-11c, OSRD-5271c; 1945.

3. "On the Estimation of the Perturbations due to Flow Around Blast Gauges"; J.K.L. MacDonald and S.A. Schaaf; AMP Note No. 22, AMG-NYU 136; 1946.

4. "Response of Air-Blast Gauges of Various Shapes as a Function of Pressure Level"; S.T. Marks; BRL Report No. 734; 1950.

5. Princeton Trailer: A mobile 24-channel cathode-ray tube recording system consisting of D.C. amplifiers, cathode-ray tube circuits, timing circuits, calibration circuits, power supplies, and auxiliary test and measuring circuits. Three-inch cathode-ray tubes are employed, the traces being photographed on 35mm film moving at speeds up to 480 inches per second. The frequency response of the D.C. amplifiers is flat to 15 KC and is down 6 db at 50 KC. The response is attenuated between 15 KC and 20 KC by filters in order to eliminate interference from radio station NSS at 17.8 KC. The equipment requires two 35 KWA generators.

It was also believed that it would be desirable to use larger charges, since the results obtained from larger charges are more reproducible.

Moreover, the previous series of tests were terminated at the 40 lb/in^2 peak pressure level, whereas air-blast gauge response data at higher pressures was desired.

It was therefore decided to retest the same gauges over the 10 to 80 lb/in^2 peak pressure range, using one-pound bare spherical pentolite charges, and to employ the White Trailer,[1] which has recording amplifiers whose frequency characteristics are excellent.

This report presents the results obtained from the second series of tests and makes a comparison with the results previously reported.

EXPERIMENTAL PROCEDURE

Essentially the same experimental procedure was followed as was used previously, although certain modifications and improvements were incorporated. These will be described.

One-pound bare spherical pentolite charges were fired at a series of predetermined distances from the air-blast gauges being tested, these distances having been selected from the "Pressure Versus Scaled Distance" graph compiled by the Terminal Ballistics Laboratory, so as to produce the desired series of peak pressures at the gauge positions (Figures 1 and 2). The charges were suspended with light cord from a steel rack having runners next to the ground so that its location could easily be adjusted. The air-blast gauges were mounted in the ends of horizontal two-foot sections of pipe, which were attached at their mid-points to the tops of upright two-by-four's with pipe clamps. This arrangement allowed the air-blast gauges to protrude from their supports, thus avoiding the possibility of reflections interfering with the records and also permitting the positions of the gauges to be adjusted easily. Both the charges and the gauges were supported at a height of five feet above level ground, this elevation having been selected as being high enough to prevent ground reflections from affecting the records and at the same time low enough to permit necessary adjustments of the gauge positions.

1. White Trailer: A mobile four-channel cathode-ray tube recording system consisting of D.C. amplifiers, cathode-ray tube curcuits, tuning circuits, calibration circuits, power supplies, and auxiliary test and measuring circuits. Nine-inch cathode-ray tubes are employed, the traces being photographed with a 6-3/8 inch lens at an opening of F 2.5, on 90mm photographic paper moving at speeds up to 480 inches per second. The frequency response of the D.C. amplifiers is flat to 80 KC. The equipment requires two 10 KWA motor generators.

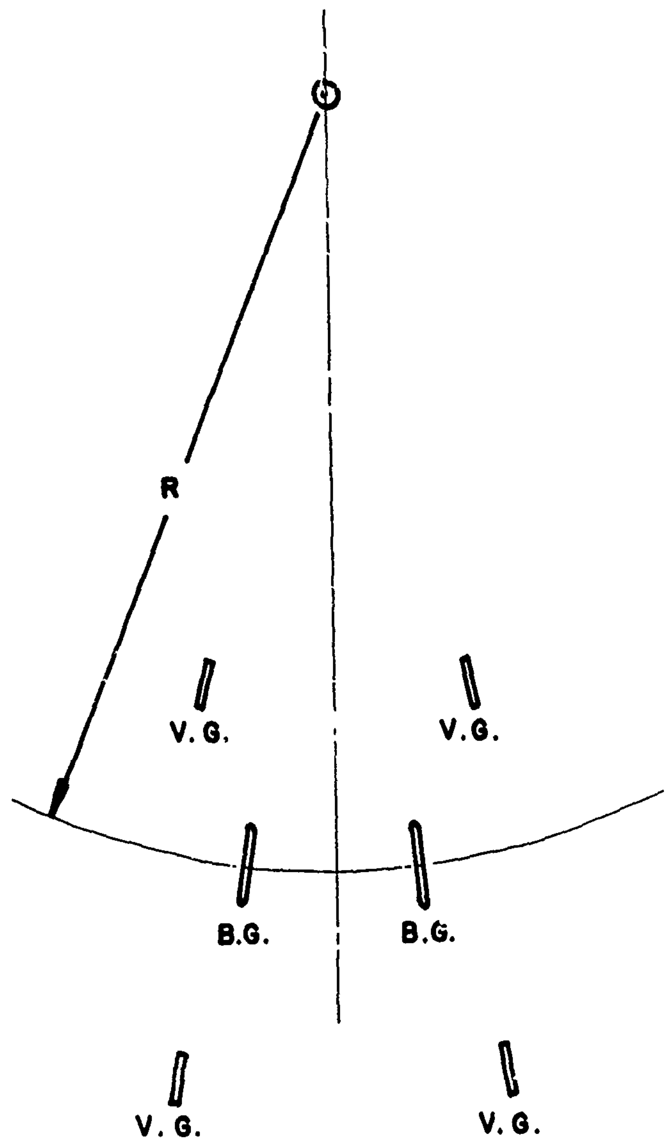


FIG. I EXPERIMENTAL TEST SETUP

V.G.: VELOCITY GAUGES; B.G.: BLAST GAUGES

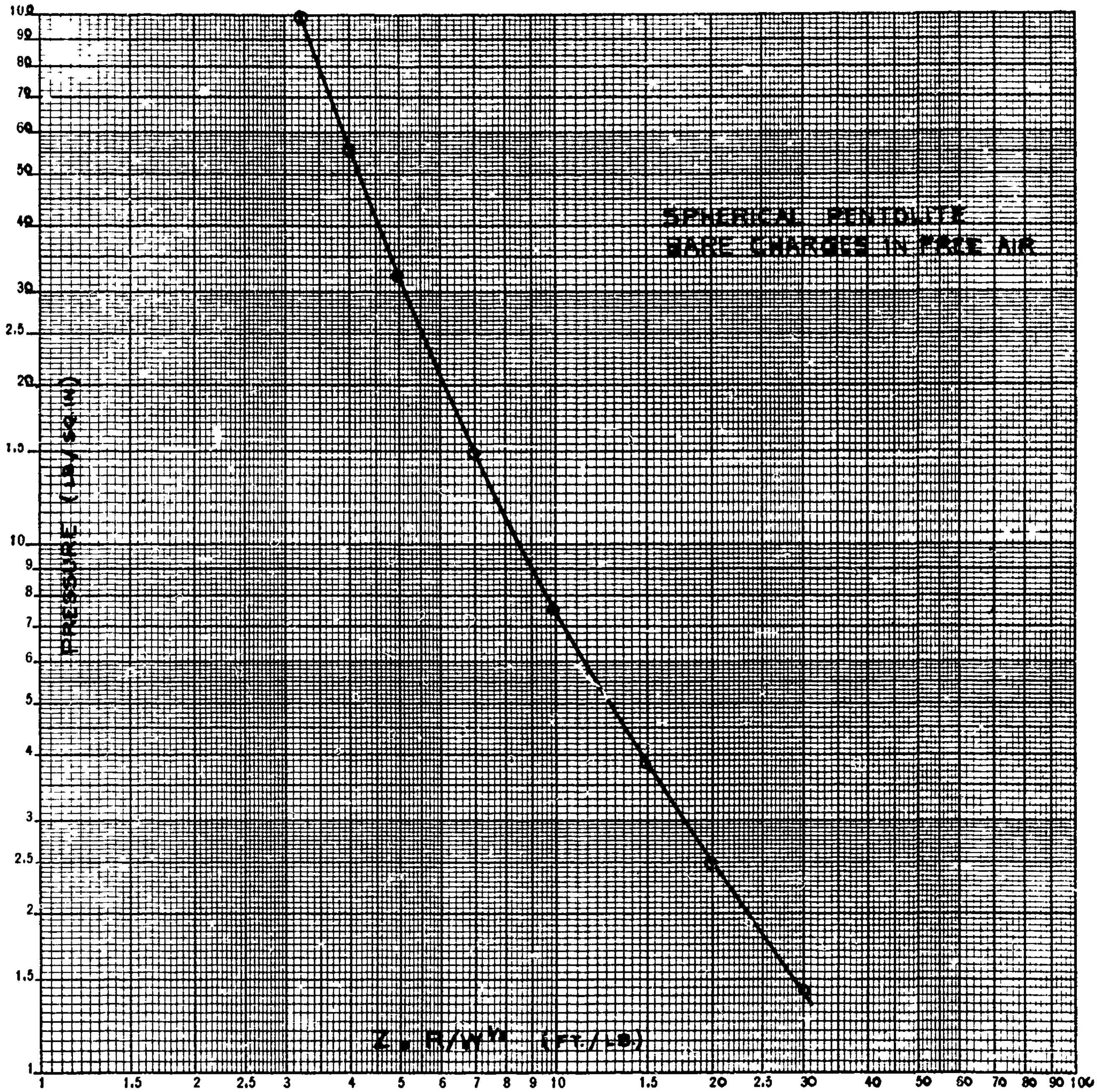


FIG. 2. PRESSURE VERSUS SCALED DISTANCE

R = DISTANCE FROM CHARGE   W = WEIGHT OF CHARGE

Included in the group of air-blast gauges tested were two BRL gauges, two experimental pancake-shaped gauges, and an experimental pencil-shaped gauge, thus making it possible to obtain data concerning a wide range of baffle shapes (Figure 3). Two air-blast gauges were tested at a time, a prerequisite for firing being that the resistances of the gauges and cables had to be not less than 500 megohms.

It was assumed that the shock waves produced were spherical at the gauge positions, and hence the blast gauges were made equally distant from the charges before each charge was fired, thus avoiding additional calculations. The distance measurements were made with a steel scale to the nearest 0.01 inch.

The two pairs of Rochelle salt velocity gauges previously employed were replaced by two pairs of barium titanate velocity gauges developed in connection with this program[1], one pair being placed on each side of the blast gauges being tested, with the forward gauges of each pair one foot ahead of the blast gauges, and the rear gauges one foot behind them.

The outputs of the gauges were fed into oscilloscopes and recorded on oscillograph recording paper. The two separate 35mm film records previously used, one for the calibration and blast gauge records and the other for the velocity gauge records, were replaced by one Eastman Kodak oscillograph paper record, Type 697, moving at 40 ft/sec. Two blast gauge channels were employed, a series of calibration steps having been recorded on these channels before each charge was fired. Two velocity channels were also employed, the outputs of the velocity gauges being applied to the horizontal plates of the oscilloscope in the form of a square wave, while the output of a crystal controlled oscillator was applied to the vertical plates. A harmonic of the oscillator was checked against radio station WWV before each group of charges was fired in order to insure timing accuracy. The arrival times of the shock-front at the velocity gauges was thus recorded in the form of rectangular pips on 10-KC symmetrical triangular traces, two microsecond reading accuracy being achieved without difficulty. This arrangement proved to be desirable because the oscillograph recording paper can be developed at the firing site right after the charge is fired, permitting immediate inspection of the results. In addition, it was found that the oscillograph recording paper was easier to read, could be read much faster, and could be read with equal accuracy.

The atmospheric pressure was recorded with a calibrated and temperature compensated aneroid barometer located at the firing site and placed at the same height as the group of air-blast gauges being tested. This barometer was checked against a precision mercury barometer at intervals to insure accuracy.

---

1. A Barium Titanate Velocity Gauge; S.T. Marks, BRL Technical Note No. 461; May 1951.

The velocity of sound was obtained by recording the temperature of the air at the firing site with a calibrated mercury thermometer making relative humidity measurements with a sling psychrometer and employing the relation[1]

$$C_o = 1088 \sqrt{1 + \frac{t}{273}} \left[1 + 0.149 \frac{P_w}{P_a} \right]$$

where C_o is the velocity of sound in air ahead of the shock,

t is the air temperature (Centigrade),

P_w is the partial pressure of water vapor in air, and

P_a is the partial pressure of the air.

A comparison of results obtained by this method and by the "firing-a-cap-method" indicates that this method produces reasonably accurate results.[2]

The peak pressures were obtained independently from the shock-front velocity measurements by the application of the Rankine-Hugoniot ideal gas relation

$$P_s = P_o \left(\frac{2\gamma}{\gamma+1}\right) \left(\frac{U^2}{C_o^{\,2}} - 1\right),$$

where P_s is the peak pressure,

P_o is the atmospheric pressure ahead of the shock,

U is the velocity of shock-front propagation,

C_o is the velocity of sound in air ahead of the shock, and

γ is 1.40 (ratio of specific heats for air).

The wind speed and direction were measured with an anemometer and weather vane in the vicinity of the firing site, and the component of the wind velocity parallel to the line from the charge to the gauges was added or subtracted from the measured shock-front velocity, depending upon its direction. Wind effects were held to a minimum by restricting firing to fairly calm days, or to days when a slight cross wind prevailed.

---

1. Final Report on the Shock Tube; J.C. Fletcher, W.T. Read, R.G. Stover, and D.K. Weiner; NDRC A-356, OSRD-6321; 1946.

2. Unpublished report: The Measurement of the Velocity of Sound in an Open Field; Marvin F. Clarke, Ordnance Engineering Laboratory, BRL, Aberdeen Proving Ground, Maryland.

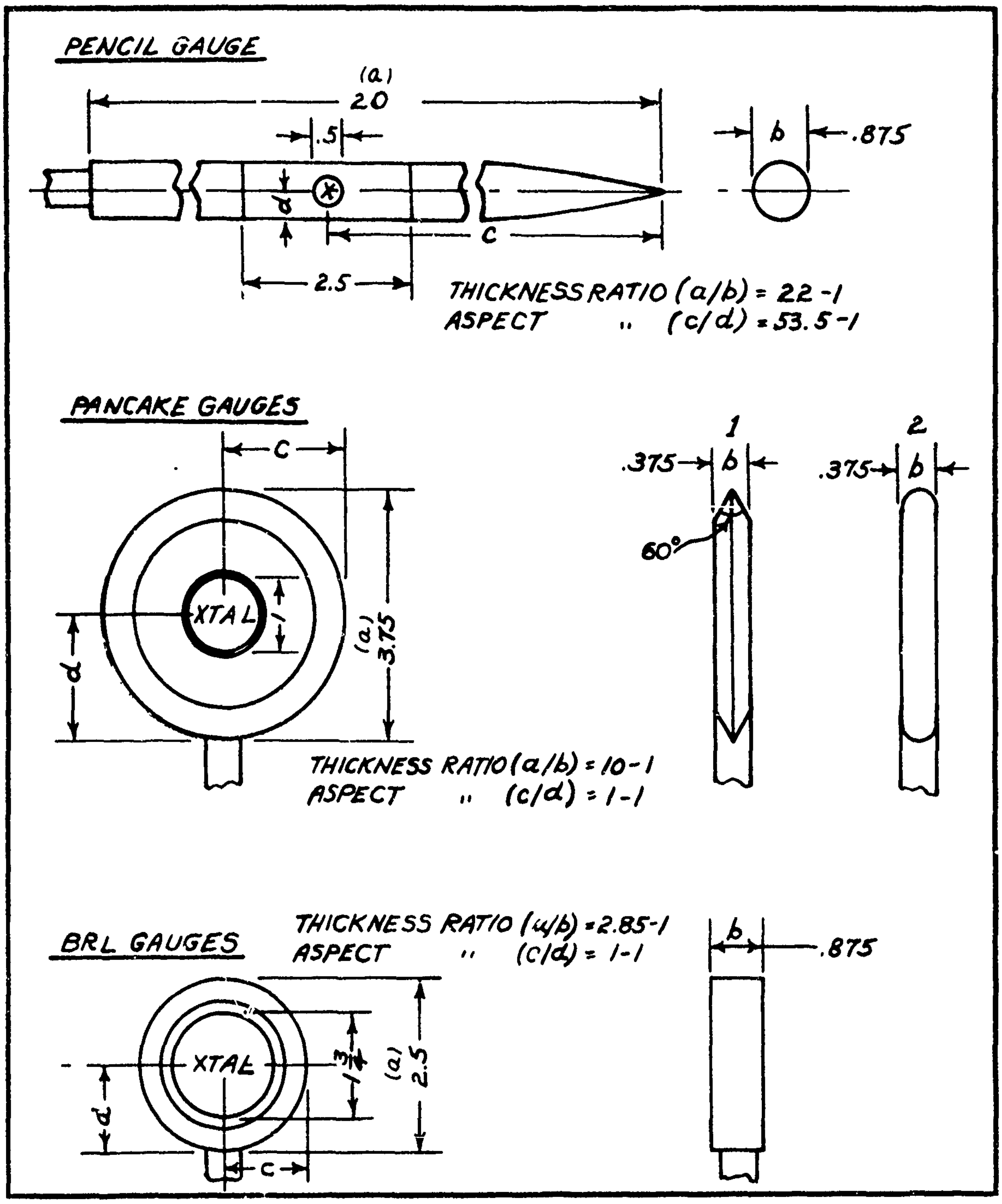
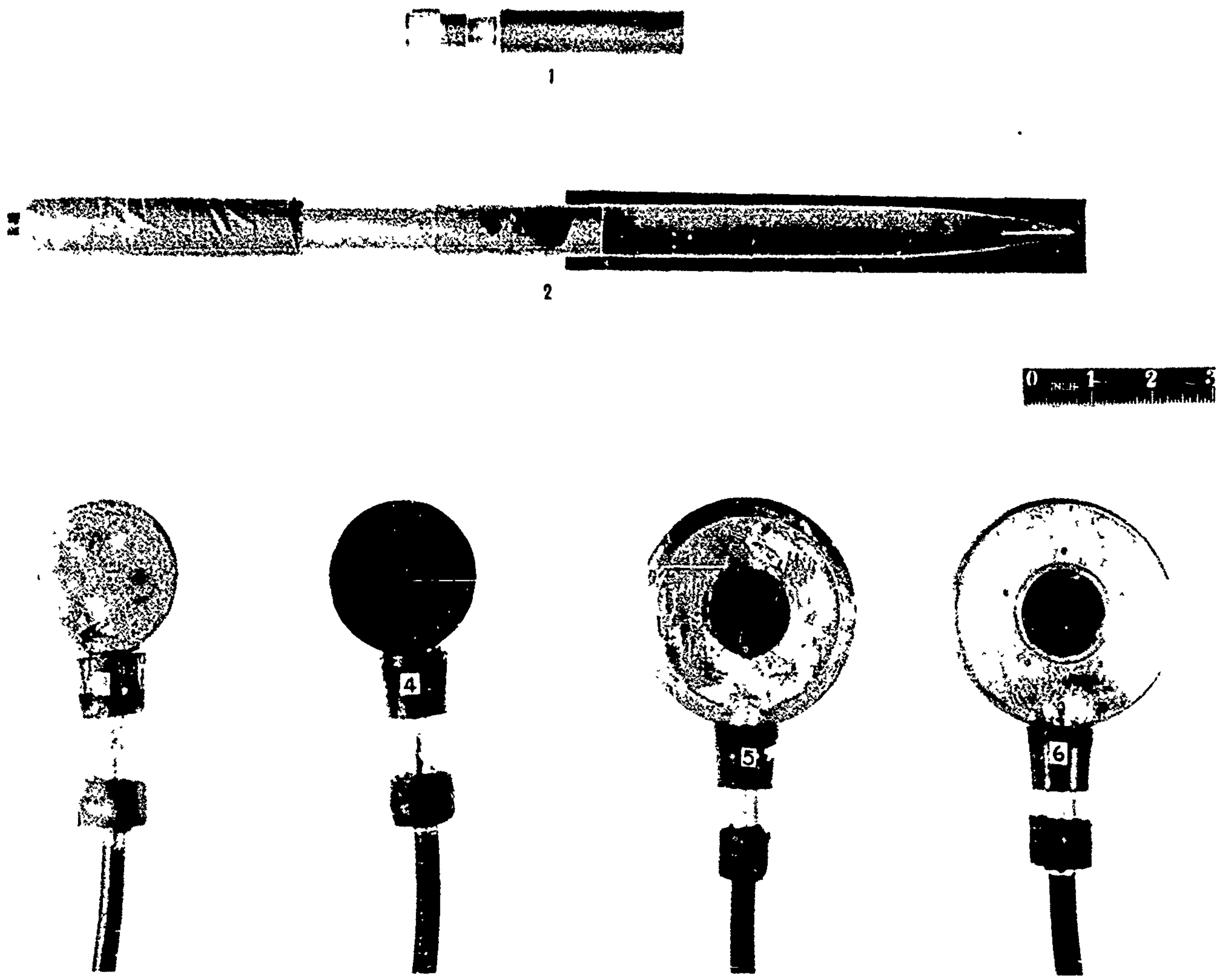

PENCIL GAUGE
(a)
20
.5
d
c
2.5
b
.875
THICKNESS RATIO (a/b) = 22-1
ASPECT " (c/d) = 53.5-1
PANCAKE GAUGES
C
XTAL
1
(a) 3.75
d
1
2
.375
b
60°
THICKNESS RATIO (a/b) = 10-1
ASPECT " (c/d) = 1-1
BRL GAUGES
THICKNESS RATIO (a/b) = 2.85-1
ASPECT " (c/d) = 1-1
XTAL
1 3/4
(a) 2.5
d
c
b
.875

FIG.3



Air-Blast Gauges. 1. Barium Titanate Velocity Gauge, 2. Pencil 1, 3. BRL T-63, 4. BRL T-66, 5. Pancake 1, 6. Pancake 2.

The distances from the charge at which these peak pressures apply ($P_s < 17$ lb/in^2) were calculated from the approximate relation[1]

$$R_v \cong R_m \left[1 - \frac{n+1}{24} \left(\frac{\Delta r}{R_m} \right)^2 \right],$$

where R_v is the distance from the charge at which the average shock velocity measured over interval Δr is equal to the instantaneous shock velocity,

R_m is the distance from the charge of the mid-point of the velocity interval,

n is the exponent in the distance-decay law when approximated by a power function, and

Δr is the length of the velocity measurement interval.

The distances from the charge at which these peak pressures apply ($P_s > 17$ lb/in^2) were calculated from the relation[2]

$$R_v = R_m \left\{ 1 - \frac{\left(\frac{\Delta r}{R_m}\right)^2 R_m^n}{16K} \left[\frac{3n-2}{2} + \left(\frac{2-n}{3} \right) \frac{K}{R_m^n} \right] \right\},$$

where R_v, R_m, n and Δr are the same as above,

K is equal to $\frac{6A}{7P_o}$,

A is equal to $\frac{Ps}{r^n}$, and

r is the distance from the center of the charge to the center of the gauge element.

The peak pressures at the air-blast gauge positions were then calculated from the relation

$$\frac{P_1}{P_2} \left(= \frac{r_2}{r_1} \right)^2$$

1,2 - Apparatus for Measurement of Air Blast of Piezoelectric Gauges; G. K. Fraenkel; NDRC A-373, OSRD-6251; 1946.

where P_1 is the peak pressure at the position where the average shock velocity over interval Δr is equal to the instantaneous shock velocity,

P_2 is the peak pressure at the gauge position,

r_1 is the distance from the center of the charge to the position where the average shock velocity over interval Δr is equal to the instantaneous shock velocity,

r_2 is the distance from the center of the charge to the center of the air-blast gauge element, and

n is the exponent in the distance decay law when approximated by a power function.

The effective dynamic gauge responses were then calculated, employing the relation[1]

$$KA = \frac{d_p E_o C_s}{d_c P_s} ,$$

where KA is the effective dynamic gauge response ($\mu\mu$ coul./lb/in^2),

d_p is the deflection resulting from P_s,

P_s is the peak pressure at the gauge position,

E_o is the calibration voltage,

d_c is the deflection resulting from E_o, and

C_s is the standard capacitance ($\mu\mu$f).

EXPERIMENTAL RESULTS

The effective dynamic KA's of the gauges tested as a function of peak pressure level are plotted in Figures 4 to 8, response curves having been fitted to the data using the method of least squares. The static calibrations of the gauges have also been included.

BRL gauges T-63 and T-66 are round unbaffled gauges of identical construction and dimensions (Figure 3), consisting of a four-crystal stack, made of 1-3/4 inch diameter tourmaline discs cemented to a steel housing, and sensitive on one side only. The ratio of the diameter to thickness of these gauges in approximately 3:1, and Figures 4 and 5 show that these gauges are subject to the greatest reductions in response of the gauges tested.

---

1. Design and Use of Tourmaline Gauges for Piezoelectric Measurement of Air Blast; A.B. Arons and C.W. Tait; NDRC A-372, OSRD-6250; 1946.

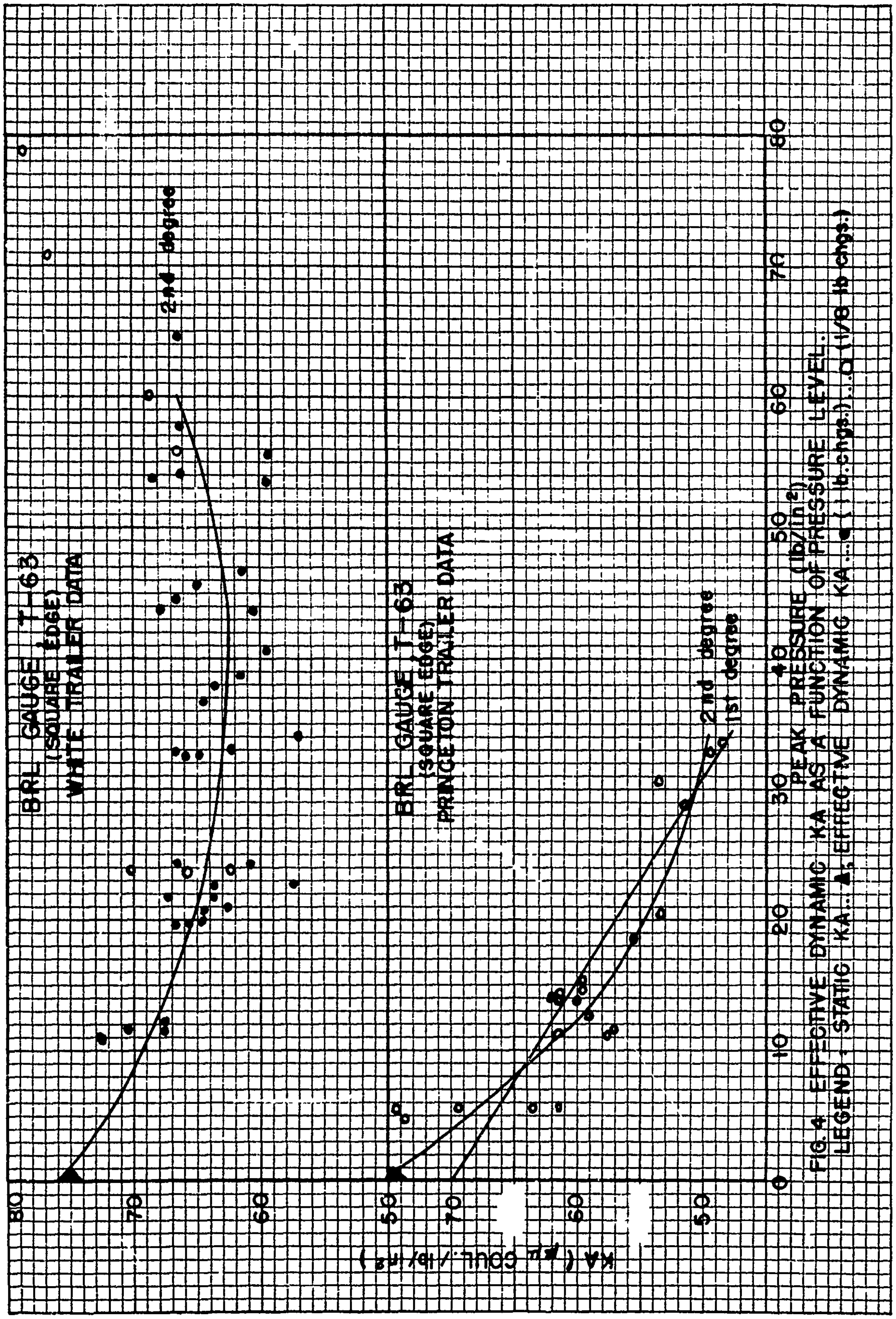


FIG. 4 EFFECTIVE DYNAMIC KA AS A FUNCTION OF PRESSURE LEVEL.
LEGEND: STATIC KA..▲, EFFECTIVE DYNAMIC KA...● (1 lb.chgs.)...○ (1/8 lb chgs.)

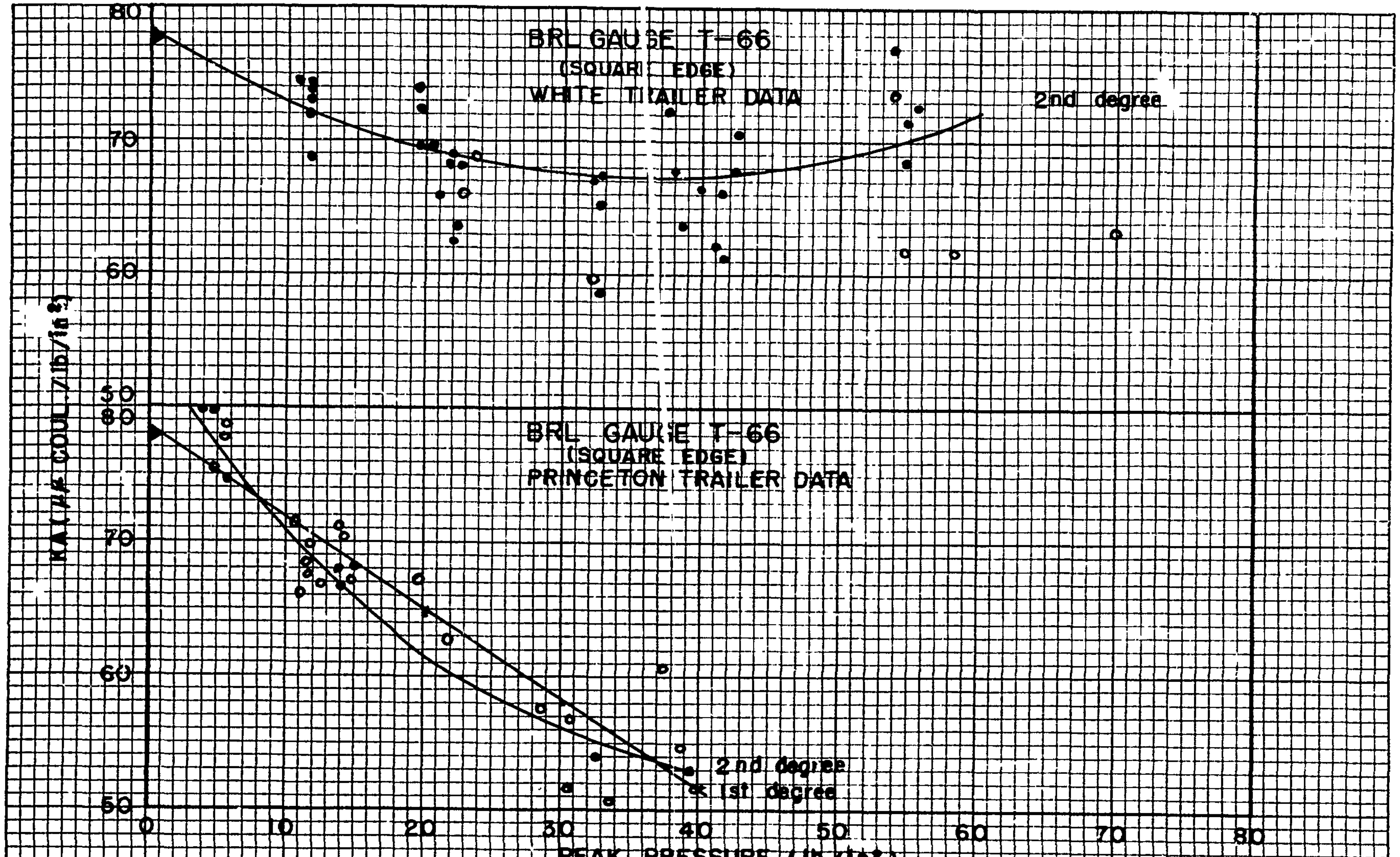


FIG.5. EFFECTIVE DYNAMIC KA AS A FUNCTION OF PRESSURE LEVEL
LEGEND: STATIC KA ... ▲; EFFECTIVE DYNAMIC KA ... ● (1 lb chgs) ... o (1/8 lb chgs)

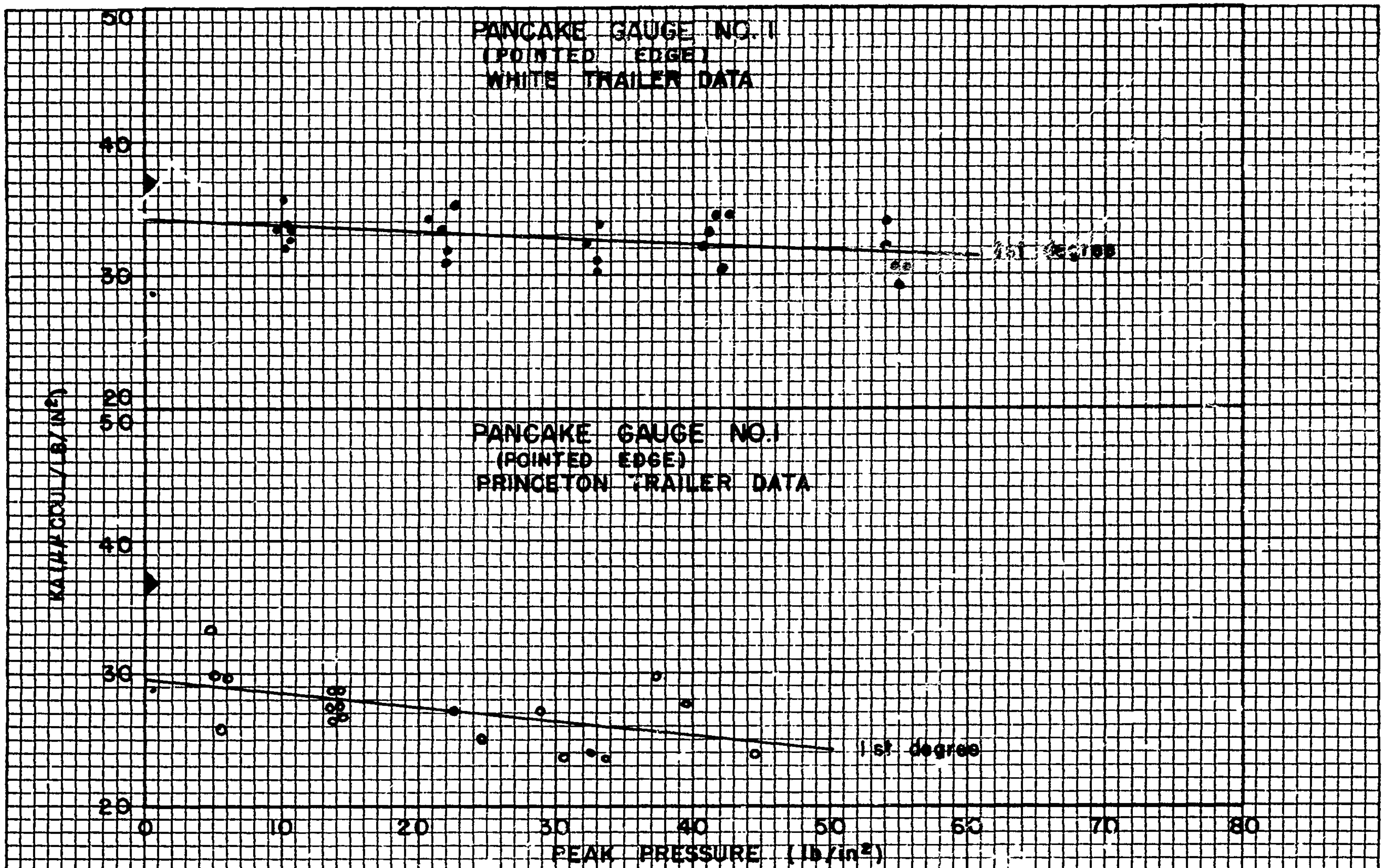


FIG. 6 EFFECTIVE DYNAMIC KA AS A FUNCTION OF PRESSURE LEVEL

LEGEND: STATIC KA ▲; EFFECTIVE DYNAMIC KA ● (1 LB CHGS.) ○ (1/8 LB CHGS.)

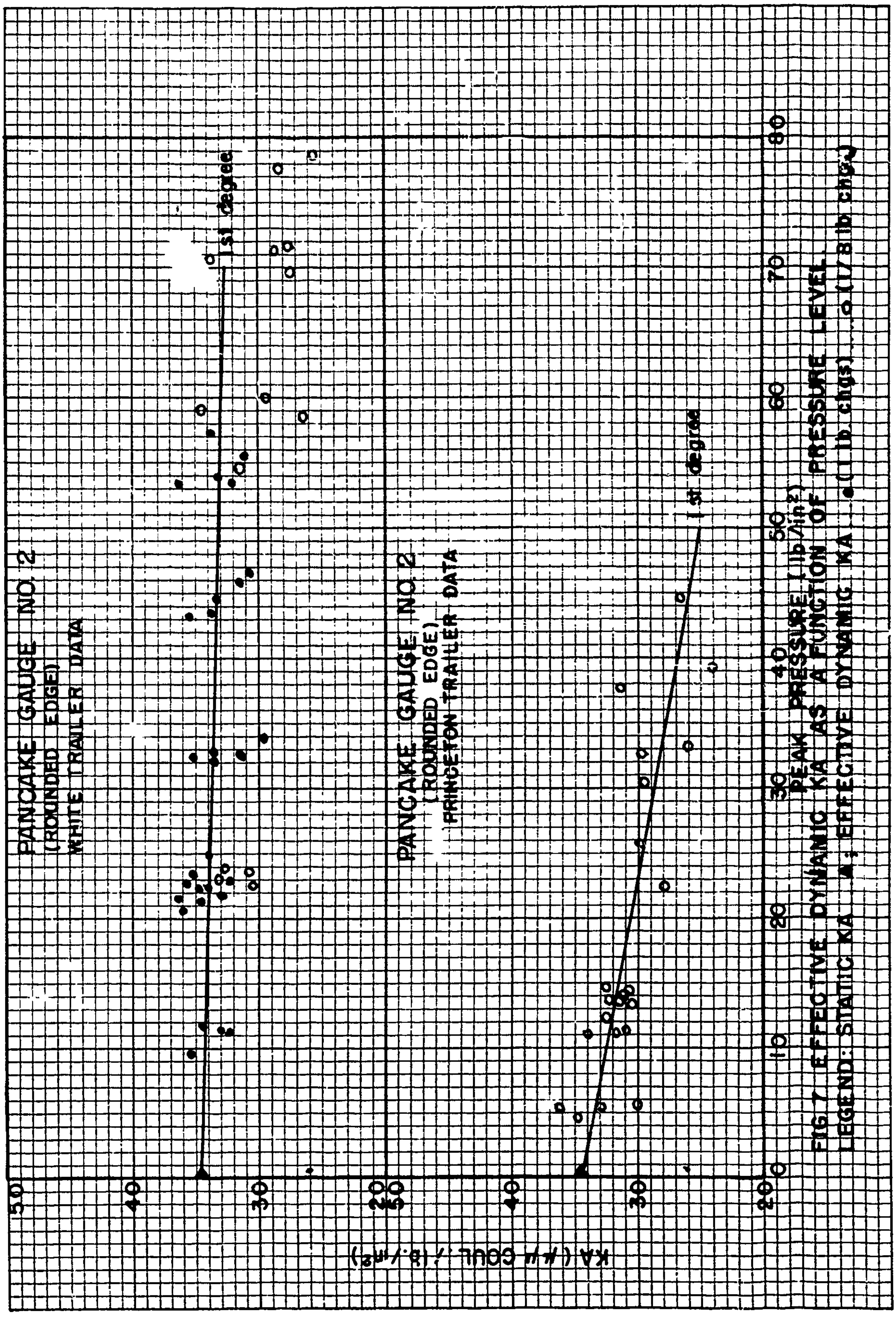


FIG 7 EFFECTIVE DYNAMIC KA AS A FUNCTION OF PRESSURE LEVEL

LEGEND: STATIC KA ▲; EFFECTIVE DYNAMIC KA ● (1 lb chgs) ○ (1/8 lb chgs)

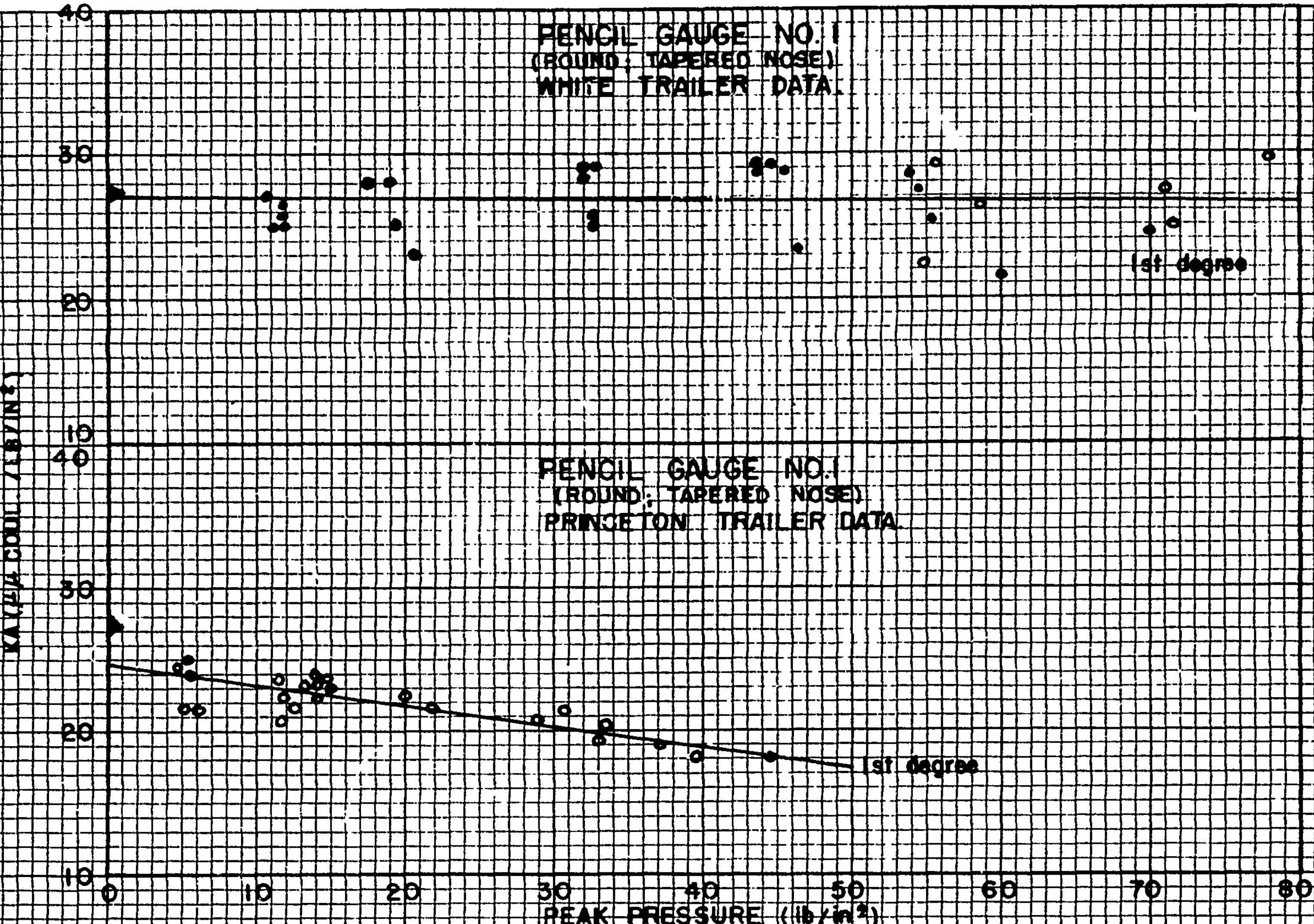


FIG. 8 EFFECTIVE DYNAMIC KA AS A FUNCTION OF PRESSURE LEVEL.
LEGEND: STATIC KA... ▲; EFFECTIVE DYNAMIC KA... ● (1LB CHGS.) ... o (1/8 LB CHGS.)

When one-pound charges were recorded on the White Trailer, the reductions in response of the BRL gauges increased up to peak pressures of 40 lb/in^2 at which point they were approximately 15 percent below the static calibrations. The response curves level off at this peak pressure level and then start to rise, the reductions in response at 57-lb/in^2 peak pressure (Mach 1), being about 10 per cent. It should be noted that the fitted second degree curves extrapolate to the static calibrations in the case of both gauges.

The BRL gauges are subject to much greater reductions in response when recording one-eighth pound charges on the Princeton trailer, the reductions in response at 40-lb/in^2 peak pressure being approximately 33 per cent below the static calibration. The fitted first degree curve extrapolates to the static calibrations in the case of BRL gauge T-66 but not in the case of BRL gauge T-63. However, application of student's "t" test[1] indicated that the deviation of the extrapolated point from the static calibration was not significant in the latter instance.

Three shots at the peak pressure level of 40 lb/in^2 on the plot of the response curve of BRL gauge T-63 for one-eighth pound charges recorded on the Princeton trailer have been deleted from the present report because it is now believed that they were in error. Similar variations occurred during the present series of tests and were found to be due to failure of the calibration capacitor to make contact with the circuit when the charge was fired. This reduced the capacitance of the circuit and caused an erroneously high response level to be recorded.

Pancake gauges Nos. 1 and 2 are round baffled gauges of similar construction and dimensions except for their edge shape, No. 1 having a pointed edge and No. 2 having a rounded edge (Figure 3). The sensitive elements of these gauges consist of two two-crystal stacks made of one-inch diameter tourmaline discs soldered to opposite sides of a central brass tab, which is an integral part of the brass baffle. These gauges are sensitive on both sides. The ratio of the diameter of the baffle to the thickness of these gauges is 10:1, a ratio which, in conjunction with the edge shape of pancake gauge No. 1, should hold the "flow-effect error" to a maximum of five per cent up to peak pressures of 35 lb/in^2 (Mach 0.8), according to the predictions of Mac Donald and Schaaf,[2] and Figures 6 and 7 show that the pancake gauges are subject to much smaller reductions in response than are the BRL gauges.

---

1. "t" test: A statistical test of Hypotheses, one of whose applications is the testing of the difference between two means. In this case, we are testing to determine whether the value of the extrapolated dynamic KA at zero peak pressure could have come from a population whose value at zero peak pressure equals the static calibration.

2. On the Estimation of the Perturbations due to Flow Around Blast Gauges; J.K.L. MacDonald and S.A. Schaaf; AMP Note 22, AMG-NYU 136; 1946

When one-pound charges were recorded on the White trailer, the reductions in response of the pancake gauges were approximately four per cent at the 40 lb/in^2 peak pressure level and six per cent at 57 lb/in^2. The first degree curve fitted to the data of pancake gauge No. 2 extrapolated to the static calibration of that gauge, but the first degree curve fitted to the data of pancake gauge No. 1 did not. Application of the t test indicated a significant difference in this case. A number of one-eighth pound charges recorded on the White trailer did not produce as high a response level as the one-pound charges in the case of pancake gauge No. 2, although the slope of a straight line passed through these points appears to be about the same.

The pancake gauges are subject to much greater reductions in response when one-eighth pound charges are recorded on the Princeton trailer, the reduction being about 20 per cent at the 40 lb/in^2 peak pressure level. Again, it is noted that the first degree curve fitted to the data of pancake gauge No. 2 extrapolates to the static calibration; while the first degree curve fitted to the data of pancake gauge No. 1 does not, the t test indicating a significant difference.

The pencil gauge is an air-blast gauge of new design, shaped like a pencil, with two six-crystal stacks made of 1/2-inch diameter tourmaline discs inserted into openings on opposite sides of the pencil at its midpoint (Figure 3). The ratio of the length of the pencil to its thickness is approximately 20:1, which should hold the flow-effect error to a very low value, and Figure 8 shows that the pencil gauge is the least subject to response errors of the gauges tested.

When recording one-pound charges on the White trailer, the response curve of the pencil gauge shows only a one per cent reduction up to the 80-lb/in^2 peak pressure level, and the fitted first degree curve extrapolates to the static calibration. The one-eighth pound charges that were included produced the same response level as the one-pound charges in this case.

In contrast, when recording one-eighth pound charges on the Princeton trailer, the pencil gauge is subject to a 22 per cent reduction at 40-lb/in^2 peak pressure. The fitted first degree curve does not extrapolate to the static calibration, the t test indicating a significant difference.

The percentage response errors as a function of peak pressure level have been tabulated in Table I and II, the effective dynamic KA's at zero peak pressure having been used as the reference point. These correspond with the static calibration in most instances.

TABLE I

Percentage Errors in Effective Gauge Response Versus Peak Pressure

One-Pound Charges, White Trailer

Gauge	10 lb.	20 lb.	30 lb.	40 lb.	50 lb.	60 lb.	70 lb.	80 lb.
Pencil 1*	0.1%	0.2%	0.3%	0.4%	0.5%	0.6%	0.7%	0.8%
Pancake 1	1.4%	2.8%	4.2%	5.7%	7.3%	8.5%	--	--
Pancake 2*	1.2%	1.4%	2.6%	3.2%	4.3%	4.6%	5.5%	--
BRL T-63*	7.6%	12.9%	15.[illegible]	16.7%	15.3%	11.3%	--	--
BRL T-66*	6.4%	10.9%	13.5%	13.5%	12.2%	7.7%	--	--

Note: Ex[illegible]polated effective dynamic KA used as the reference point.

* Extrapolated dynamic KA corresponds with static calibration.

TABLE II

Percentage Errors in Effective Gauge Response Versus Peak Pressure

One-Eighth Pound Charges, Princeton Trailer

Gauge	10 lb.	20 lb.	30 lb.	40 lb.	50 lb.	60 lb.	70 lb.	80 lb.
Pencil 1	4.6%	11.7%	18.2%	23.9%	30.0%	--	--	--
Pancake 1	3.7%	7.8%	11.2%	15.2%	18.7%	--	--	--
Pancake 2*	6.4%	11.9%	17.4%	22.6%	28.1%	--	--	--
BRL T-63*	15.8%	26.8[illegible]	32.3%	--	--	--	--	--
BRL T-66	15.9%	27.6%	34.7%	38.2%	--	--	--	--

Note: Extrapolated effective dynamic KA used as the reference point.

* Extrapolated dynamic KA corresponds with static calibration.

An additional comparison of these percentage response errors for the respective air-blast gauges is shown in Figures 9 and 10.

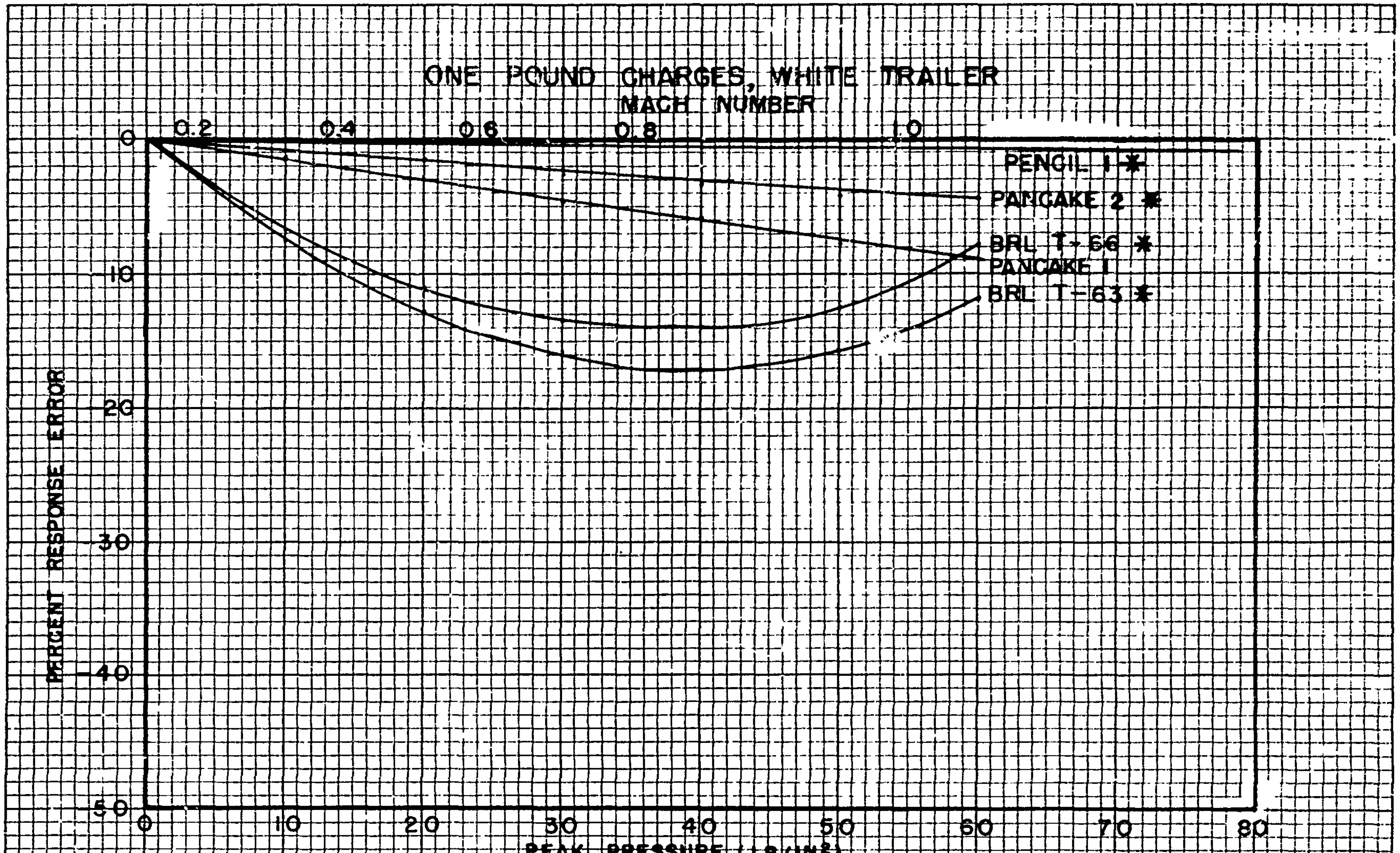


FIG. 9 ERROR IN GAUGE KA AS A FUNCTION OF PEAK PRESSURE LEVEL.
NOTE: EXTRAPOLATED DYNAMIC KA USED AS THE REFERENCE POINT.
* EXTRAPOLATED DYNAMIC KA CORRESPONDS WITH STATIC CALIBRATION.

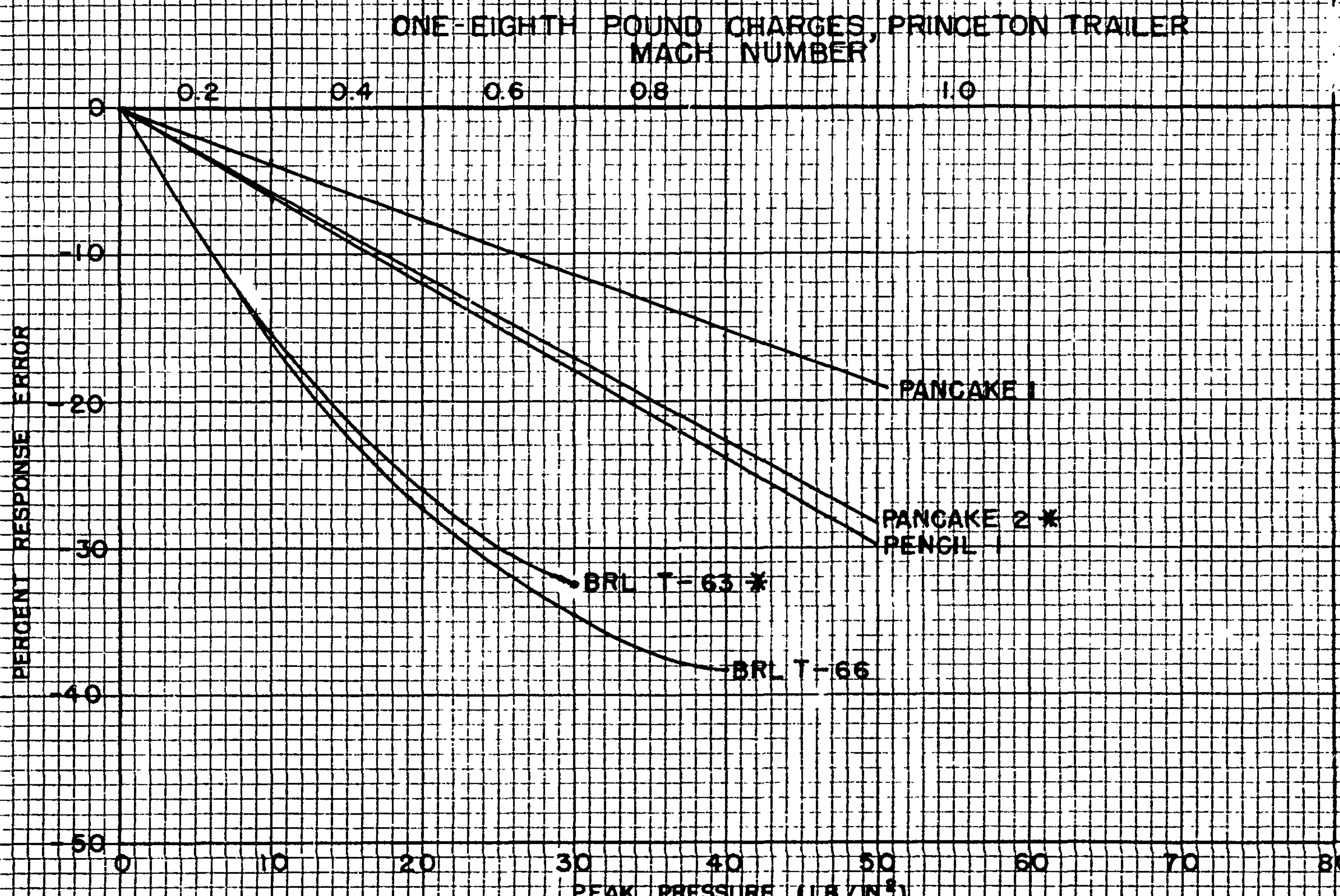


FIG. 10 ERROR IN GAUGE KA AS A FUNCTION OF PEAK PRESSURE LEVEL.
NOTE: EXTRAPOLATED DYNAMIC KA USED AS THE REFERENCE POINT.
✱ EXTRAPOLATED DYNAMIC KA CORRESPONDS WITH STATIC CALIBRATION.

INTERPRETATION OF EXPERIMENTAL RESULTS

Figures 4 to 8 reveal that in a number of instances discrepancies exist between the static and the effective dynamic calibrations when the latter are extrapolated to zero peak pressure, the most outstanding case being that of Pancake gauge No. 1. This gauge was rebuilt during the tests, and the possibility existed that the static calibration of the gauge had changed. However, a static calibration run on this gauge following completion of the tests duplicated the original calibration; and this result, together with the fact that the fitted curves extrapolate to the static calibrations in seven out of eight other cases, would seem to indicate that the data are in error in those instances where agreement between the extrapolated effective dynamic calibration and the static calibration does not exist. These discrepancies may possibly be caused by inaccurate velocity measurements.

A reduction in the percentage response errors represents an improvement in the recording characteristics of the gauges and equipment. A comparison of Figures 9 and 10 shows that the percentage response errors of all gauges tested were considerably reduced when the White recording trailer was substituted for the Princeton recording trailer, and one-pound charges were employed instead of one-eighth pound charges.

All factors during the two series of tests were identical with the exceptions of the velocity gauges, the charge size, and the recording trailers. It is therefore logical to assume that one or more of these factors was responsible for the observed reductions in the magnitudes of the percentage response errors.

The use of different type velocity gauges during the two series of tests is not believed to have been an important factor, since tests have shown that the shock-front velocities recorded by the two types of gauges compare favorably.

The difference in charge size, however, could make a significant difference, since one pound charges produce shock durations which are twice as long as those produced by one-eighth pound charges. In effect, this would reduce the gauge-size errors by a factor of two.

The response characteristics of the recording trailers could also make a significant difference. Assuming that the rise times of the pressure-time records correspond approximately with the gauge-crossing times, and that the frequency response of the amplifiers should be flat to ten times the rise-time frequency for faithful reproduction, a rough calculation would indicate the need for amplifiers whose frequency responses are flat to at least 100,000 cycles.

Examination of the frequency response curves of the White and Princeton trailer amplifiers shows that those of the White trailer are flat to 80,000 cycles while those of the Princeton trailer are flat to only 40,000 cycles. Moreover, filters installed in the latter trailer to eliminate interference from radio station NSS at 17,800 cycles have the effect of attenuating the response and causing phase shift, which limits the flatness of response of these amplifiers to approximately 15,000 cycles. See Table III.

TABLE III

Desirable Versus Actual Amplifier Frequency Response

Type of Gauge	Freq. Res. Should be Flat to:	White Trailer Is Flat to:	Princeton Trailer Is Flat To:
		10-lb/in^2 Peak Pressure	
Pencil	83,400	80,000	15,000
Pancake	41,700	80,000	15,000
BRL	23,800	80,000	15,000
		60-lb/in^2 Peak Pressure	
Pencil	139,500	80,000	15,000
Pancake	69,500	80,000	15,000
BRL	39,600	80,000	15,000

It would therefore appear that the frequency response characteristics of the White Trailer amplifiers are reasonably adequate for recording blast-gauge outputs with fidelity. Those of the Princeton Trailer amplifiers, however, would appear to be inadequate.

A comparison of Figures 9 and 10 shows that approximately the same differences exist between the percentage response error curves of the respective gauges on both graphs. This is illustrated in Tables IV and V, in which the differences between the curves of BRL gauge T-63 and pancake gauge No. 2 have been tabulated. These gauges were selected for comparison purposes because their extrapolated dynamic KA's corresponded with their static calibrations on both test series.

TABLE IV

Differences in Percentage Response Errors

One-Pound Charges, White Trailer

Gauge	10 lb.	20 lb.	30 lb.	40 lb.
BRL T-63*	7.5%	12.7%	16.0%	17.0%
Pancake 2*	1.0%	1.7%	2.0%	3.0%
Difference	6.5%	11.0%	14.0%	14.0%

* Extrapolated dynamic KA corresponds with static calibration.

TABLE V

Differences in Percentage Response Errors

One-Eighth Pound Charges, Princeton Trailer

Gauge	10 lb.	20 lb.	30 lb.	40 lb.
BRL T-63*	15.5%	26.5%	32.5%	36.0%
Pancake 2*	6.0%	11.5%	17.0%	23.0%
Difference	9.5%	15.0%	15.5%	13.0%

* Extrapolated dynamic KA corresponds with static calibration.

Figure 9 shows that the pencil and pancake gauges, both of which require an amplifier which is flat to a higher frequency than would be necessary for the BRL gauges, are recorded with small percentage response errors by the White trailer. It would therefore appear that some factor other than frequency response must be responsible for the much greater reductions in response of the BRL gauges. Other possible causes of these differences in response are the gauge-size error and the flow-effect error, which were discussed in the introduction. If these differences in response were caused solely by the gauge-size error, the differences between the response curves should become greater and greater with increased peak pressure level, since the shock durations are progressively reduced while the diameter of the gauge element remains constant. The flow-effect error, on the other hand, presumably might increase up to a certain peak pressure level and then decrease, which is the type of effect observable in the case of the BRL gauges, as shown in Figure 9. No doubt, both of these errors are present.

One other possible cause of response error should be mentioned. Tourmaline is subject to a "pyroelectric effect" unless it is insulated against the temperature rise in blast waves, a change of 1° C having the same effect as a pressure of 200 lb/in^2, with the effects being of opposite sign.[1] The type and thickness of the insulating coating varies in the case of the gauges included in these tests, but it is believed to be sufficient in all cases to eliminate this effect as a source of error.

Casual inspection of Figures 4 to 8 would seem to indicate that all of the gauges tested are subject to approximately the same relative scatter regardless of element size or baffle dimensions.

Application of the variance ratio or "F" test[2] to the data from one-pound charges recorded on the White trailer shows that the average relative errors are of the same order of magnitude for all of the gauges tested. See Table VI.

TABLE VI

Average Relative Errors in KA

One-Pound Charges, White Trailer

Type of Gauge	Crystal Diameter	Baffle Dimensions	Average Relative Errors
Pencil 1	0.5"	20-1	3.90
Pancake 1	1.0"	10-1	3.54
Pancake 2	1.0"	10-1	3.45
BRL T-63	1.7"	3-1	3.58
BRL T-66	1.7"	3-1	3.19

A study was also made of the regression of relative scatter on peak pressure by the method of least squares. The results indicated that the relative scatter increases slightly with increased peak pressure level in the case of pancake gauge No. 1, but not in the cases of the other gauges tested.

1. Blast Pressures and Momenta from Some Large Bombs; E.B. Wilson, Jr., and W. D. Kennedy; NDRC, OSRD-3046; 1943

2. F test: A statistical test of the hypothesis that two samples may come from normal populations with equal variances.

It would therefore appear that the scatter in the data is independent of the gauge size and shape, as well as peak pressure level, and must be attributed to some other factor, or combination of factors.

An effort was made to relate the errors in KA to errors in P_s (peak pressure). However, the correlation was not found to be significant.

It is logical to assume that gauges of the same physical dimensions, containing the same size sensitive elements, and insulated in a similar manner, should be subject to the same percentage response errors.

BRL gauges T-63 and T-66 are identical in every way, and Figures 9 and 10 show that their percentage response error curves are in general agreement with this hypothesis.

Pancake gauges Nos. 1 and 2 are identical except for their edge shape. The percentage response error curves of these gauges, as shown in Figure 9 for one-pound charges, are also in reasonable accord with this hypothesis. However, their percentage response error curves, as shown in Figure 10 for one-eighth pound charges, are not in such good agreement. This is due to the variation in the extrapolated KA of Pancake gauge No. 1.

In view of the differences between the percentage response error curves of the BRL gauges, as shown in Figures 9 and 10, it would appear that the accuracy of these curves is limited to a 4% spread at the 60-lb/in^2 peak pressure level.

Consequently, while the percentage response error curves of the pancake gauges, as shown in Figure 9, make it appear that pancake gauge No. 2 (rounded edge) is least subject to percentage response error, this is not necessarily true since the spread between these curves also amounts to 4% at the 60-lb/in^2 peak pressure level.

Moreover, the percentage response error curves of the pancake gauges, as shown in Figure 10, make it appear that pancake gauge No. 1 (pointed edge) is least subject to response error.

Application of the "t" test indicates that the slopes of the response curves of both pancake gauges are not significantly different from zero. It would therefore appear that the difference in edge shape of these gauges produced no significant difference in their responses.

By applying similar reasoning to the position of the percentage response error curves of the pencil gauge with reference to the curves of the pancake gauges in Figures 9 and 10, it cannot logically be said that there is a significant difference in the responses of these two types of gauges.

This is supported by application of the "t" test, which shows that the slopes of the percentage response error curves of both the pencil and pancake gauges are not significantly different from zero.

It should be noted that the data on the pencil gauge were taken using both 12 and 8 inch nose sections, and no discernible difference in the responses of the gauge occurred. The ratio of the length of the pencil gauge to its thickness is 30:1 using the 12 inch nose, and 22:1 using the 8-inch nose; and it may be that a nose section somewhat shorter than 8 inches could be used without affecting the response of the gauge.

ESTIMATED RESPONSE ERRORS

It was believed that it would be of interest, in view of predictions made in the literature, to calculate the values of the response errors that are believed to be involved in blast gauge recordings and then compare the totals of these estimated response errors with the response errors actually recorded during these tests.

This has been done at two peak pressure levels, using the data obtained by recording one-pound charges on the White trailer, and one-eighth pound charges on the Princeton trailer. The extrapolated dynamic KA at zero peak pressure has been used as the reference point. This corresponds with the static calibration in most instances.

The estimated flow-effect errors were calculated using the relation employed by Schaaf[1]

$$\delta_p = \frac{70\ M^2}{\sqrt{1 - M^2}} \cdot C_{p,o}\ ;$$

where δ_p is the percentage flow-effect error,

M is the Mach number behind the shock-front, and

$C_{p,o}$ is the mean pressure coefficient over the gauge surface.

(The application of this equation to a pencil shape is a doubtful procedure.)

Next the estimated gauge-size errors were calculated using the relation[2]

1 Estimation of Perturbations due to Flow Around Blast Gauges with Spheroidal Shapes; S.A. Schaaf; AMG-NYU 144; 1946.

2 "Design and Use of Piezoelectric Gauges for Measuring Large Transient Pressures"; A.B. Arons and R.H. Cole; Review of Scientific Instruments; January 1950.

$$\frac{a}{c\,\theta}$$

where a is the radius of the sensitive element,

c is the velocity of shock-front propagation, and

θ is the initial decay time of the trace.

(This relation applies when the ratio of half the gauge-crossing time to the initial decay time of the recorded trace is less than 1/5.)

The estimated high frequency amplifier response errors were then calculated from the relation[1]

$$\Delta = \beta \ln \left[1 + (1 - \epsilon^{-\alpha/\beta}) / \alpha \right],$$

where Δ is the fractional error recorded by the amplifier,

β is equal to K/θ,

K equals RC equals $1/2\,\pi\, f_c$

RC is the time constant of the input circuit,

f_c is the frequency at which the amplifier response is down to 70 per cent of its mid-band response,

θ is the initial decay time,

ϵ is the constant 2.71828,

α is γ/θ, and

γ is the gauge crossing time.

The peak pressures at the blast-gauge positions, as obtained from the two-point velocity measurements, were reduced by the estimated flow-effect error percentages in order to obtain the peak pressures acting upon the respective blast-gauge sensitive elements.

The peak pressures effective upon the respective blast-gauge sensitive elements were then reduced by the sums of the estimated gauge-size error and the estimated high amplifier response error percentages so as to obtain the peak pressures which the respective blast-gauges should have recorded.

The percentage differences between the peak pressures at the blast-gauge positions, as determined by the two-point velocity method, and the peak pressures which the respective blast gauges should have recorded, were then calculated.

The results of these calculations are presented in Tables VII and VIII, along with the response errors which were actually recorded during these tests.

1. "Design and Use of Piezoelectric Gauges for Measuring Large Transient Pressures"; A.B. Arons and R.H. Cole; Review of Scientific Instruments; January 1950.

TABLE VII

Estimated Response Errors Versus Recorded Response Errors

One-Pound Charges, White Trailer

Type of Gauge	Crystal Diameter	Baffle Dia. to Thickness	Estimated Flow Effect Errors	Estimated Gauge-Size Errors	Estimated Freq. Res. Errors	Estimated Response Errors	Recorded Response Errors
			11.5 lb/in² (Mach .39)				
Pencil 1*	0.5"	20:1	0.54%	2.36%	1.40%	4.35%	0.2%
Pancake 1	1.0"	10:1	1.37%	4.95%	1.00%	7.22%	1.4%
Pancake 2*	1.0"	10:1	1.37%	4.95%	1.00%	7.22%	1.0%
BRL T-63*	1.7"	3:1	5.15%	8.00%	0.80%	13.0%	8.6%
BRL T-66*	1.7"	3:1	5.15%	7.55%	0.75%	12.9%	7.4%
			32.0 lb/in² (Mach .77)				
Pencil 1*	0.5"	20:1	3.2%	3.96%	2.3%	9.5%	0.5%
Pancake 1	1.0"	10:1	6.2%	8.8%	1.9%	16.2%	4.2%
Pancake 2*	1.0"	10:1	6.2%	8.8%	1.9%	16.2%	2.5%
BRL T-63*	1.7"	3:1	29.3%	12.7%	1.3%	39.2%	13.4%
BRL T-66*	1.7"	3:1	29.3%	12.7%	1.3%	39.2%	16.5%

* Extrapolated dynamic KA corresponds with static calibration.

TABLE VIII

Estimated Response Errors Versus Recorded Response Errors

One-Eighth Pound Charges, Princeton Trailer

Type of Gauge	Crystal Diameter	Baffle Dia. to Thickness	Estimated Flow-Effect Errors	Estimated Gauge-Size Errors	Estimated Freq. Res. Errors	Estimated Response Errors	Recorded Response Errors
13.86 lb/in^2 (Mach .448)							
Pencil 1	0.5"	20:1	0.9%	4.5%	2.2%**	7.5%	8.5%
Pancake 1	1.0"	10:1	1.9%	7.5%	1.4%**	10.6%	5.5%
Pancake 2*	1.0"	10:1	1.9%	7.8%	1.6%**	11.1%	8.0%
BRL T-63*	1.7"	3:1	7.2%	12.4%	1.1%**	19.6%	20.2%
BRL T-66	1.7"	3:1	7.2%	13.9%	1.3%**	21.6%	21.0%
28.86 lb/in^2 (Mach .723)							
Pencil 1	0.5"	20:1	3.2%	6.9%	3.7%**	13.4%	17.3%
Pancake 1	1.0"	10:1	6.3%	11.7%	2.5%**	19.6%	11.0%
Pancake 2*	1.0"	10:1	6.3%	12.0%	2.5%**	20.0%	16.5%
BRL T-63*	1.7"	3:1	23.8%	15.8%	1.5%**	36.9%	32.0%
BRL T-66	1.7"	3:1	23.8%	15.2%	1.6%**	36.5%	34.0%

*Extrapolated dynamic KA corresponds with static calibration.

**Effects of filter attenuation not taken into consideration.

INTERPRETATION OF ESTIMATED RESPONSE ERROR RESULTS

An examination of Table VII reveals that close agreement between the totals of the estimated response errors and the recorded response errors has not been achieved in the case of one-pound charges recorded on the White trailer, the recorded response errors being considerably less than the estimated response errors.

Better agreement is shown in Table VIII, which presents the results of the estimated response error calculations having to do with one-eighth pound charges recorded on the Princeton trailer, but the agreement would not be nearly as good if the effects of filter attenuation could be calculated and taken into consideration.

The lack of close agreement between the estimated response errors and the recorded response errors when one-pound charges were recorded on the White trailer casts doubt upon the validity of the respective response error calculations, the indication being that the magnitude of one or more of the response errors has been over estimated.

Of the response errors which have been considered, the indications are that the gauge-size and frequency response error calculations are the most valid, while the validity of the flow-effect error calculations remains in doubt. In this connection, Hicks and Armstrong[1] have recently reported that a series of wind tunnel tests have indicated the magnitude of the flow-effect errors affecting blast gauges to be only one-third to one-half the values predicted by MacDonald and Schaaf.

The possibility also exists that the response levels of the gauges, as calculated, are erroneously high. This effect could result if the corrections applied to the peak pressures obtained from the velocity measurements are invalid, this conclusion having recently been reached by Cooney and Sperrazza.[2] (These corrections were applied to account for the fact that the average velocity is not effective at the center of a two-point velocity measurement interval when an exponential decay is involved.)

A large reduction in the magnitudes of the estimated flow-effect errors to agree with the results reported by Hicks and Armstrong, plus elimination of the peak pressure corrections in accordance with the conclusion of Cooney and Sperrazza, would bring about good agreement between the estimated response errors and the recorded response errors in the case of one-pound charges recorded on the White Trailer.

1. Aerodynamic Calibration of Blast Gauges; E.P. Hicks and A.H. Armstrong; Armament Research Establishment Report (British); 1950.

2. The Position at which the Velocity of a Blast Wave Equals the Average Velocity over an Interval; Irene M. Cooney and Joseph Sperrazza; BRL Memorandum Report No. 541; May, 1951.

CONCLUSION

The information obtained through the carrying out of these tests may be summarized as follows:

1. A large reduction in the percentage response errors of all gauges tested occurred when amplifiers with excellent frequency response characteristics (flat to 80,000 cycles) were substituted for amplifiers having poor frequency response characteristics (flat to 15,000 cycles), and one-pound charges were used instead of one-eighth pound charges.

2. Approximately the same percentage response error differences between the respective gauges were obtained from both series of tests, with the pencil and pancake gauges being greatly superior to the BRL gauges in linearily of response.

3. The prediction of MacDonald and Scaaf, that a minimum baffle diameter to thickness ratio of 10:1 is desirable, has been confirmed over the peak pressure range from 10 to 80 lb/in^2.

4. No significant difference was found between the responses of pancake gauges identical in every way except for their edge shape, one having a rounded edge and the other a pointed edge ($\cap, \wedge$).

5. The responses of gauges having a pencil shape and those having a pancake shape were not found to be significantly different. (The length to thickness ratio of the pencil gauge was 20:1, while the diameter to thickness ratio of the pancake gauge was 10:1.)

6. No significant difference was found between the responses of pencil gauges having length to thickness ratios of 30:1 and 20:1 (crystal stack in side of pencil).

7. Curves fitted to the data using the method of least squares extrapolated to the static calibrations in most instances.

8. All gauges tested, regardless of size, shape, or applied peak pressure level, were found to produce the same relative scatter.

9. No correlation was found between errors in dynamic gauge KA and errors in P_s (peak pressure).

10. Attempts to estimate the response errors of blast gauges from theoretical considerations failed to produce good agreement with the recorded response errors, the recorded response errors being considerably less than the estimated response errors. However, recently reported information would appear to make good agreement possible.

With reference to future programs, it would be of interest to conduct a series of field test specifically designed to determine the magnitude of the flow-effect error. D.C. amplifiers whose frequency response is flat to 100,000 cycles should be employed, so as to reduce the frequency response error to a minimum. Then by testing an air-blast gauge both with and without a baffle at a given peak pressure level, the approximate magnitude of the flow-effect error could be determined, since the gauge-size error would be constant, and any difference in response would be due to the flow-effect error alone. The baffle should have a minimum diameter to thickness ratio of 10:1.

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1. References:

a. Ballistic Research Laboratory Memorandum Report No. 397, "An Improved Tourmaline Air Blast Gage", by T. D. Carr and M. A. Bakinowski, October 1945, AD number 494667, UNCLASSIFIED, enclosed.

b. Ballistic Research Laboratories Memorandum Report No. 1778, "Detonation Pressure Measurements in TNT and OCTOL", by R. Jameson and A. Hawkins, August 1966, AD number 802251, UNCLASSIFIED, enclosed.

c. Ballistic Research Laboratory Memorandum Report No. ARBRL-MR-03115, "Blast Computations over a Hemicylindrical Aircraft Shelter", by J. Wortman, July 1981, AD number B058960, UNCLASSIFIED, enclosed.

d. Ballistic Research Laboratory Memorandum Report No. ARBRL-MR-03125, "Combinatorial Geometry Computer Models of Sitting and Standing Crew Personnel" by L. R. Kruse and C. H. Lee, August 1981, AD number B060185, UNCLASSIFIED, enclosed.

e. Ballistic Research Laboratories Report No. 734, "Response of Air Blast Gauges of Various Shapes as a Function of Pressure Level", by S. T. Marks, August 1950, AD number 801219, UNCLASSIFIED, enclosed.

f. Ballistic Research Laboratories Report No. 775, "Response of Air Blast Gauges of Various Shapes to One-Pound Spherical Pentolite Charges as a Function of Pressure Level", by S. T. Marks, September 1951, AD number 801726, UNCLASSIFIED, enclosed.

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